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The use of freshwater macrophytes as a resource in sustainable agriculture

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ABSTRACT

Freshwater macrophytes include different groups of plants that are capable of growing in or very close to aquatic environments (spermatophytes, pteridophytes and bryophytes). These plants play a fundamental role in their ecosystems, regulating biogeochemical cycles, hydrology and sediment dynamic. Currently, many exotic freshwater macrophytes are being anthropogenically introduced into new ecosystems, posing a serious problem as a consequence of their massive and uncontrolled growth. Despite this, these plants can have different uses, such as biomarkers, phytoremediators, producers of metabolites of interest, or biomass formers for the production of feed, biofuels, pellets or ceramics. In this sense, the use of freshwater macrophytes *in vivo*, as fresh tissues, dry matter, compost, vermicompost, anaerobic digestate, liquid extracts or biochar has reported important benefits in different crops, promoting plant growth, increasing yield, reducing use of chemical fertilizers or reducing the diseases incidence. These benefits are the consequence of different mechanisms of action of the use of macrophytes as an agricultural resource, such as the contribution of nutrients, the improvement of the microbiota and soil structure, the elimination of heavy metals and pollutants, or the presence of antimicrobial compounds in their tissues. This review proposes the use of the biomass of these macrophytes, whose uncontrolled growth is an environmental problem, as an agricultural resource with important agricultural, environmental and economic benefits. A total of 118 published papers were analyzed and discussed.

1. Introduction

According to estimates made by the United Nations, the world population will have been reached 9.7 billion people by the year 2050, which would require an increase of 70% in food productivity (FAO, 2009). This population would reach 11.2 billion people in the year of 2100, requiring an increase of up to 200% (Crist et al., 2017). According to these projections, providing food to the planet's population is one of the key challenges for today's world, being the only way to ensure food security in the immediate future (Baer-Nawrocka and Sadowski, 2019). Therefore, the current rates of population growth make it essential to develop new strategies for sustainable food production (Poveda, 2021).

Conventional high-yield agriculture focuses on the use of agricultural chemicals (fertilizers and pesticides) and water and soil resources in a way that is very harmful to the environment (Plumecocq et al., 2018). In particular, the use of chemical fertilizers and pesticides in the world is currently 200 and 3.5 million tons per year, respectively (Sharma et al., 2019; Kang et al., 2022). Their massive use causes serious problems in the agro-system, such as damage to soil microflora and microfauna, or hinder the absorption of important mineral nutrients by plants (Sharma et al., 2019; Kang et al., 2022). In addition, they cause water pollution, which causes serious environmental and health damage (Basheer, 2018a,b).

Within the Sustainable Development Goals (SDGs), sustainable agriculture is considered as a key piece for global development (Janker et al., 2018). The concept of sustainable agriculture must be approached from three different and interrelated perspectives, such as economics stability, social stability and ecological/environmental sustainability (Farooq et al., 2019). Therefore, the search for environmental-friendly alternatives based on a circular economy is fundamental in the necessary development of sustainable agriculture (Poveda, 2021). One of these alternatives involves the use of new fertilizers to replace chemical fertilizers, such as nanofertilizers, biodegradable polymer-based fertilizers or biochar-based fertilizers (Calabi-Floody et al., 2018).

Organic fertilizers include all sources of slow-release plant nutrients formed from living organisms (Singh et al., 2020; Shaji et al., 2021). The most widely used include compost, biochar, manure, guano, or green manures, being fertilizers capable of mitigating the risk of

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eutrophication, contamination of groundwater and over-fertilization (Singh et al., 2020; Shaji et al., 2021). The role of organic fertilizers in sustainable agricultural systems and in improving plant productivity includes increased soil porosity and aeration, increased water infiltration rate, decreased acidity, increased diversity and quantity of beneficial macro- and micro-organisms, and increased nutrient content (Singh et al., 2020).

The objective of this review is to compile all the existing results so far in the use of freshwater macrophytes as green manures with benefits in crop growth, tolerance against abiotic stresses and defense against pathogens and pests, representing a good alternative in the development of sustainable agriculture; moreover, discussing their benefits, mechanisms of action and forms of application. This review represents the first document compiling all the existing literature to date on the use of freshwater macrophytes as an agricultural resource, providing an important discussion on the topic in a comprehensive and orderly manner.

2. Freshwater macrophytes

Freshwater macrophytes, hydrobionts or aquatic plants include all those members of the kingdom Plantae that grow in water medium or close to water, with the exception of algae, considered as microphytes in these ecosystems (rivers, basins, lakes) (Soloviy and Malovanyy, 2019). This group of macrophytes includes free floating, floating but rooted, submerged, and amphibian plants, within the spermatophytes, pteridophytes (ferns and fern allies) and bryophytes (mosses, liverworts and hornworts), being vascular less than 2% of aquatic plants (Bornette and Puijalon, 2009; Soloviy and Malovanyy, 2019). Macrophytes are important primary producers in freshwater ecosystems, serving as habitats for periphytons, invertebrates (including zooplankton), and vertebrates (fish and frogs). This group of plant species plays a key role in biogeochemical cycles, such as organic carbon production, extracting carbon dioxide from the air and water and fixing it in photoassimilates (photosynthesis), or nitrogen and phosphorous mobilization, absorbing excess nutrients from the water and preventing major environmental problems such as eutrophication. Furthermore, due to their ability to modify water flows, macrophytes freshwater are capable of modifying hydrology and sediment dynamic, although there may be other factors involved. Therefore, they are essential components for freshwater ecosystems (Bornette and Puijalon, 2009).

Regarding the freshwater macrophytes world distribution, there is a hitherto general-accepted hypothesis that indicates that most aquatic macrophytes have broad world distributions, which has been confirmed by a recent study on the diversity and endemism patterns of 3457 macrophyte species (Murphy et al., 2019). In this respect, the Neotropics and the Orient have the richest ecozones in terms of macrophyte species, while the Sahara/Arabian deserts and some areas of the Arctic have the lowest macrophyte diversity (Murphy et al., 2019). Despite this, there are differences in the communities of freshwater macrophytes that inhabit different ecosystems, as a consequence of the action of environmental variables and human impact (Elo et al., 2018). Freshwater ecosystems are threatened all over the world due to important factors derived from human activity, such as climate change, altered water regimes, catchment land-use changes, eutrophication (run-off from agricultural, industrial or urban areas), and establishment of invasive plants. Due to the importance of these aquatic systems in ecosystems and the ability of freshwater macrophytes to act as ecological bioindicators, due to the presence/absence of certain species in certain ecosystems, it is essential to improve our knowledge of the ecology and management of native and alien plants to address threats to freshwater in order to protect and restore aquatic habitats (Hofstra et al., 2020).

Biological invasion in freshwater ecosystems by alien macrophytes can cause significant damage, due to the development of cascading effects on functional integrity and structural organization of the ecosystem. At present there are several freshwater macrophyte species described as dangerous alien plants, among which *Eichhornia crassipes*, *Egeria densa*, *Trapa natans*, *Hygrophila polysperma*, *Lagarosiphon major*, *Myriophyllum aquaticum* or *Salvinia molesta* stand out for their distribution and worldwide importance (Brundu, 2015). In this sense, it is important to highlight that many of the recent invasions occur due to human activities linked with international trade for ornamental purposes in ponds and aquarium. The main damages of the introduction of exotic macrophytes in new ecosystems derive from its rapid growth and dispersion, which causes the introduction of allelopathic chemicals that release into water, decreased penetration of light, increased turbidity and decreased dissolved oxygen, due to the decomposition of the large plant biomass formed (Hassan and Nawchoo, 2020).

3. Possible uses of freshwater macrophytes

Despite the possible ecological problems derived from the massive growth of native and alien freshwater macrophytes, there are numerous fully developed uses today, such as biomarkers, phytoremediators, producers of metabolites of interest (antimicrobials, herbicides, insecticides, drugs), or biomass formers for the production of feed, biofuels, pellets, or ceramics, as has been compiled for alien plants such as *E. crassipes* (Su et al., 2018). The study of macrophyte communities present in a freshwater ecosystem can provide data on the ecological status of that site (Kuhar et al., 2011; Ciecierska and Kolada, 2014) and the quality of its waters (Ceschin et al., 2010; Kolada, 2010), indicating important aspects such as eutrophication (Kolada et al., 2014; Han and Cui, 2016) or the presence of anthropogenic pollutants (Nunes et al., 2014; Alkimin et al., 2019).

The use of macrophytes as freshwater phytoremediation agents has been widely compiled by several authors, both through the establishment of populations in these water bodies and through the manufacture of absorbent materials from their biomass, mechanisms referred to as phytoextraction (Yongabi et al., 2018; Bashir et al., 2020). In this sense, many different species of freshwater macrophytes are capable of removing heavy metals from the water, such as arsenic (Xue and Yan, 2011; Zhang et al., 2012), cadmium (Xie et al., 2013; Dogan et al., 2018), lead (Singh et al., 2010; Dogan et al., 2018), chromium (Augustynowicz et al., 2010) or uranium (Markich, 2013; Li et al., 2019), hydrocarbons (Pondei et al., 2018), pesticides (Alencar et al., 2020), including herbicides as glyphosate (Pérez et al., 2017; da Silva-Santos et al., 2020), industrial and urban wastes as wood preservatives (Demers et al., 2020), cosmetics (Guedes-Alonso et al., 2020), or organic matter (Queiroz et al., 2017), veterinary antibiotics (Xian et al., 2010), or drugs (Pi et al., 2017; Guedes-Alonso et al., 2020). In this respect, many of the macrophytes are considered to be hyperaccumulators, with phytoextraction rates above 1%, e.g. with heavy metals (Yongabi et al., 2018).

Furthermore, freshwater macrophytes are capable of producing secondary metabolites of interest to various biotechnology industries. As examples, the production of antibacterial agents against harmful cyanobacteria blooms (phenols, flavonoids and tannins) (Tazart et al., 2019), insecticides against Diptera larvae (flavonoids, tannins and alkaloids) (Ugya et al., 2019), anticancer (unidentified) (Hassanien et al., 2018), antidiarrhoeal, wound healing, antioxidant and anti-acetylcholinesterase, antineoplastic, anti-inflammatory, analgesic or antipyretic agents (alkaloids, cardiac glycoside, glycosides, tannins and flavonoids) (Abu, 2017).

On the other hand, the great capacity of freshwater macrophytes to produce large amounts of biomass can be of great use for different industries. Due to their protein (11–32%) and lipid (3–17%) content, freshwater macrophytes are good feed ingredients in aquaculture, providing a good range of amino acids. In a current situation of global protein demand, the use of macrophytes as a substitute for fishmeal has the potential to revolutionize aquaculture (Naseem et al., 2021). Moreover, as a consequence of their carbohydrate content, harvested freshwater macrophytes can be used efficiently in the production of biogas by fermentation (more than 7 mL of biogas per g of macrophyte biomass) (Fernandes et al., 2019; Röhl et al., 2019). These biogases include biohydrogen, produced by a dark fermentation process using the microbe *Enterobacter cloacae* (an C5 and C6 sugars using organism) (Karthikeya et al., 2020), and methane, also by dark fermentation and using bacteria from the macrophyte biomass (Grasset et al., 2019). Solid biofuels have also been produced by hydrothermal carbonization of biomass from macrophytes in a high-pressure reactor under subcritical temperatures of 240–320 °C, an alternative fuel called hydrochar (Rather et al., 2017a,b). In addition to all the indicated applications, the alien freshwater macrophytes biomass, such as *E. crassipes*, can be used for the manufacture of charcoal briquettes by carbonization at 500 °C and with a high calorific value (16.6 MJ/kg) (Carnaje et al., 2018), and even ceramic materials by pressing and burned at 1000 °C (Delaqua et al., 2020).

4. Freshwater macrophytes applications in agriculture

Freshwater macrophytes can be used as a resource in agriculture in various ways and provide different benefits. The infographic in Fig. 1 summarizes in a schematic way all these uses and benefits, which are compiled in detail in Table 1.

4.1. Nutrients supply

The macrophytes establishment in agricultural irrigation reservoirs and streams is related to a better health of the agroecosystem, since they absorb excess nutrients, avoiding eutrophication (Mebane et al., 2014). In this sense, it has been reported that the existence of macrophytes in agricultural irrigation reservoirs and streams implies an improvement in water quality, including content in N and P, and an increase in the productivity of crops such as maize (90%) or eggplant (40%) (Akponikpè et al., 2011; Owamah et al., 2014).

As indicated previously, freshwater macrophytes play a fundamental role in nutrient cycling in aquatic ecosystems, representing an important nutrient reservoir for possible use as organic fertilizer in agriculture, especially in N and P (Demars and Edwards, 2007; Human et al., 2015). In freshwater ecosystems, the release of nutrients present in the tissues of macrophytes occurs naturally due to the decomposition of organic matter by different fungi and bacteria (Zhao et al., 2020), which must act on agricultural soils to make nutrients available to crops.

In rice fields, the controlled application of different freshwater macrophytes has been carried out *in vivo* due to their ability to actively supply nutrients such as N. *Azolla* is a genus of aquatic fern capable of fixing atmospheric nitrogen through symbiosis with the cyanobacterium *Anabaena azollae*. The application of *Azolla* in rice fields supposes an increase in the growth of rice plants as a consequence of a higher contribution of N, and of P and Ca when the macrophytes die (Ahmad and Tariq, 2021). Similarly, the suspended aquatic carnivorous plant *Urticularia inflexa* contributes N in rice fields through symbiosis with *Anabaena* (Wagner and Mshigeni, 1986).

The application of fresh tissues from different freshwater macrophytes, such as *Hydrilla verticillata* (waterthyme) or *Phragmites australis* (common reed), has been shown to be capable of increasing the productivity of crops such as maize, due to the contribution of nutrients to the soil, including N, P, K, Mg and Ca (Mamolos et al., 2011; Jain and Kalamdhad, 2018b; Jha, 2021). If this biomass is applied to the crop in dry matter form, as has been done with *Eichhornia crassipes* (water hyacinth), the contribution of N and P causes an increase in stem height and diameter, and shoot and root fresh and dry mass of maize plants (Dos Anjos et al., 2018).

The use of compost from freshwater macrophyte biomass is the one that has been reported by the most studies so far, due to the contribution of organic matter and nutrients (N, P and K), highlighting the *E. crassipes* species (Farias et al., 2013; Singh and Kalamdhad, 2015; Bondoc, 2020), *H. verticillata* (Jain and Kalamdhad, 2018a; Matsuoka et al., 2018), *Pistia stratiotes* (water lettuce) (Farias et al., 2013), or *Ceratophyllum demersum* (hornwort) (Matsuoka et al., 2018). Through the contribution of N, an increase in the crop yield of radish has been reported due to the use of compost from *E. crassipes* or *Egeria densa* (the large-flowered waterweed) (Martínez-Nieto et al., 2011), in addition to an increase in plant growth and photosynthetic activity in *Prunus serrulata*, *Castanea crenata*, *Quercus acutissima* and rapeseed with compost from *P. australis* or *Typha angustifolia* (narrowleaf cattail) (Song, 2017; Song and Song, 2019). Other composts are an important source of P, reducing the use of chemical P in crops such as sugarcane, tomato, bell pepper or eggplant, using biomass from *Brachiaria mutica* (para-grass), *Ludwigia peruviana* (primrose willow), *Panicum repens* (torpedograss) or *P. stratiotes* from rainwater collection ponds (Shukla et al., 2020). However, composts from freshwater macrophytes are capable of promoting plant growth and crop productivity by providing a whole set of nutrients, such as N, P, K, Ca and Mg. In this sense, there are studies carried out on crops such as *Lens*

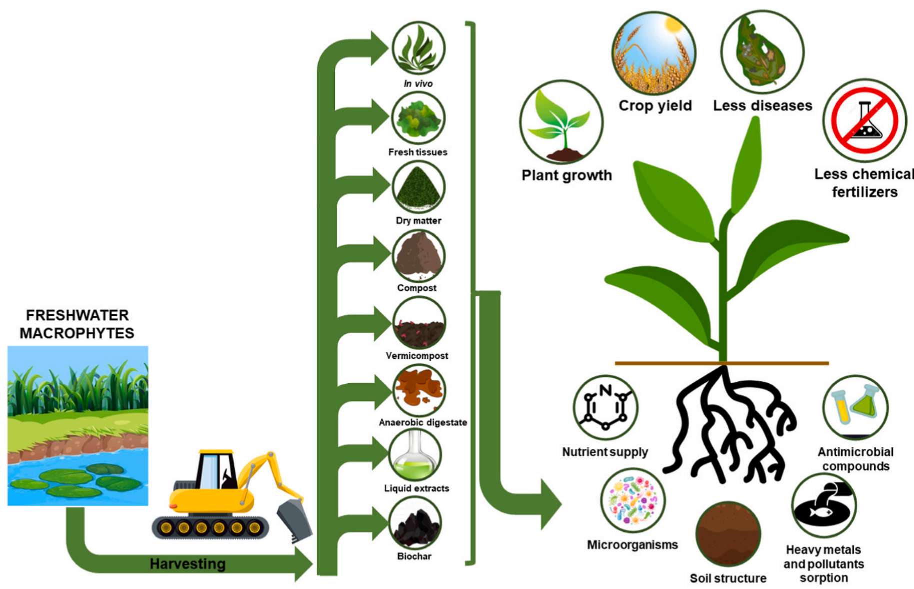

Fig. 1. Infographic on the use of freshwater macrophytes as a resource in agriculture, indicating its form of application, the benefits for crops and the mechanisms of action involved.

Table 1
Freshwater macrophytes used as resources in agriculture, indicating their form of use, the reported effects on crops and the mechanisms of action involved.

SPECIES	APPLICATION FORM	CROP	EFFECT	MECHANISMS	REFERENCE
Arundo donax	Compost: 1:2 v/v	*Lens culinaris*	Increased plant growth	Nutrients supply	Kouki et al. (2016)
Azolla spp.	Vermicompost	Eggplant	Increased plant growth and yield	Nutrients supply	Gandhi and Sundari (2012)
	In vivo: 7500 kg/Ha	Rice	Increased plant growth	N, P and Ca supply	Ahmad and Tariq (2021)
	Compost: 30000 kg/Ha	Wheat Maize Rapeseed	Increased crop yield	N, P and Ca supply	Ahmad and Tariq (2021)
A. caroliniana *A. filiculoides* *A. pinnata*	*In vivo*	Rice	–	Heavy metals sorption	Ahmad and Tariq (2021)
A. pinnata	Vermicompost	–	–	N, P and K supply	Najar and Khan (2013)
Brachiaria mutica	Compost	Sugarcane	Reduction in the use of chemical P	P supply	Shukla et al. (2020)
Ceratophyllum demersum	Vermicompost	–	–	N, P and K supply	Najar and Khan (2013)
	Compost	–	–	N supply	Matsuoka et al. (2018)
	Compost: 23.25 g/soil L (plots)	–	–	Increased quantity and diversity of phosphate solubilizing bacteria in soil	Matsuoka et al. (2019)
	Compost: 23.25 g/soil L (plots)	*Brassica rapa* var. *perviridis*	Increased plant growth	Presence of plant growth promoting rhizobacteria	Matsuoka et al. (2020)
Eichhornia spp.	Vermicompost	Eggplant	Increased plant growth and yield	Nutrients supply	Gandhi and Sundari (2012)
	Liquid fertilizer: 18.000 kg/Ha	–	–	N and P supply	Kolhe and Singh (2019)
E. crassipes	Compost	–	–	Nutrients supply	Chukwuka and Omotayo (2008)
	Compost	–	–	N and P supply	Mees et al. (2009)
	Compost: 1:1 (v/v)	Radish	Increased crop yield	N supply	Martínez-Nieto et al., 2011
	Compost	–	–	N, P and K supply	Farias et al. (2013)
	Vermicompost	–	–	Nutrients supply	Kannadasan et al. (2013)
	Compost: 5000 Kg/Ha	Maize	Increased plant growth	N and P supply	Osoro et al. (2014)
	Compost	–	–	N and P supply	Singh and Kalamdhad (2015)
	n-Butyl alcohol leaf extract	–	Antimicrobial effect against *Bacillus subtilis*, *Alternaria alternata* and *Colletotrichum gloeosporioides*	Phenols, alkaloids, flavonoids, glycosides, tannins, and terpenoids	Haggag et al. (2017)
		Wheat	Antimicrobial effect against *Pyrenophora teres*		
	Dry matter: 75% (v/v)	Maize	Increased plant growth	N and P supply	Dos Anjos et al., 2018
	Compost: 10–30% (v/v)	*Libidibia ferrea*	Increased plant growth	Heavy metals sorption	Gaudencio et al. (2018)
	Biochar	–	–	Heavy metals sorption	Li et al. (2018)
	Compost: 5000 kg/Ha	Maize	Increased yield	N, P, K, Mg and Ca supply	Atere and Olayinka (2019)
	Compost: 39 g/soil Kg (plots)	Chinese cabbage	Not indicated	Not indicated	Han et al. (2019)
	Vermicompost	–	–	N, P and K supply	Kurian and Joseph (2019)
	Biochar: 4% (v/v)	Rice (*Pokkali*)	Increased plant growth	Nutrients supply	Najmudeen et al. (2019)
	Compost: 5000 kg/Ha	Soybean	Not described	Increased nodulation and N_2 fixation	Atere et al. (2020)
	Compost	–	–	N and P supply	Bondoc (2020)
	Compost: 33% (w/w)	Chinese cabbage	Increased plant growth	Improved soil structure	Rakotoarisoa et al. (2020)
	Compost	–	–	–	Shyam et al. (2020)
Egeria densa	Compost: 1:1 (v/v)	Radish	Increased yield	N supply	Martínez-Nieto et al., 2011
Elodea nuttallii	Anaerobic digestate	–	–	P supply	Stabenau et al. (2018)
Hydrilla verticillata	Compost	–	–	Nutrients supply	Jain and Kalamdhad (2018a)
	Fresh tissues	–	–	N, P, K, Mg and Ca suppy	Jain and Kalamdhad (2018b)
	Compost	–	–	N supply	Matsuoka et al. (2018)
		–	–		

(*continued on next page*)

Table 1 (*continued*)

SPECIES	APPLICATION FORM	CROP	EFFECT	MECHANISMS	REFERENCE
	Compost: 23.25 g/soil L (plots)			Increased quantity and diversity of phosphate solubilizing bacteria in soil	Matsuoka et al. (2019)
	Compost: 23.25 g/soil L (plots)	*Brassica rapa* var. *perviridis*	Increased plant growth	Presence of plant growth promoting rhizobacteria	Matsuoka et al. (2020)
Ipomoea carnea	Compost	–	–	–	Shyam et al. (2020)
Ludwigia peruviana	Compost	Tomato Bell pepper Eggplant	Reduction in the use of chemical P	P supply	Shukla et al. (2020)
Panicum repens	Compost	Tomato Bell pepper Eggplant	Reduction in the use of chemical P	P supply	Shukla et al. (2020)
Phragmites australis	Fresh tissues	–	–	N and P supply	Mamolos et al. (2011)
	Compost: 1400 g/m^2	*Prunus serrulata* *Castanea crenata*	Increased photosynthetic activity	N supply	Song, 2017
	Compost	Rapeseed *Quercus acutissima*	Increased plant growth and chlorophyll content	N supply	Song and Song (2019)
	Biochar	–	–	Pollutants sorption (hydrocarbons)	Wang et al. (2020)
Pistia stratiotes	Compost	–	–	N, P and K supply	Farias et al. (2013)
	Compost	Rice Sorghum	Increased plant growth	N, P, K and Si supply	Bhadha et al. (2016)
	Compost	Tomato Bell pepper Eggplant	Reduction in the use of chemical P	P supply	Shukla et al. (2020)
Polygonum hydropiperoides	Compost	Tomato Bell pepper Eggplant	Reduction in the use of chemical P	P supply	Shukla et al. (2020)
Potamogeton maackianus	Compost	–	–	N supply	Matsuoka et al. (2018)
	Compost: 23.25 g/soil L (plots)	–	–	Increased quantity and diversity of phosphate solubilizing bacteria in soil	Matsuoka et al. (2019)
	Compost: 23.25 g/soil L (plots)	*Brassica rapa* var. *perviridis*	Increased plant growth	Presence of plant growth promoting rhizobacteria	Matsuoka et al. (2020)
Salix caroliniana	Compost	Tomato Bell pepper Eggplant	Reduction in the use of chemical P	P supply	Shukla et al. (2020)
Salvinia molesta	Vermicompost: 2–20% (w/w)	Cucumber *Abelmoschus esculentus* *Vigna radiata*	Increased germination, plant growth and N contents	N supply	Hussain et al. (2018)
Thalia dealbata	Biochar	–	–	Pollutants sorption (drugs)	Li et al. (2015)
Trapa natans	Vermicompost	–	–	N, P and K supply	Najar and Khan (2013)
Typha spp.	Compost	Tomato Bell pepper Eggplant	Reduction in the use of chemical P	P supply	Shukla et al. (2020)
T. angustifolia	Compost: 1400 g/m^2	*Prunus serrulata* *Castanea crenata*	Increased photosynthetic activity	N supply	Song, 2017
	Compost	Rapeseed *Quercus acutissima*	Increased plant growth and chlorophyll content	N supply	Song and Song (2019)
T. domingensis	Compost	–	–	N, P and K supply	Farias et al. (2013)
T. latifolia	Compost: 1:2 v/v	*L. culinaris*	Increased plant growth	Nutrients supply	Kouki et al. (2016)
Urticularia inflexa	*In vivo*	Rice	–	N supply	Wagner and Mshigeni (1986)
Zostera muelleri	Biochar	–	–	–	Macreadie et al. (2017)
Not identified	Vermicompost	–	–	N, P and K supply	Najar and Khan (2012)
	Vermicompost: 6 T/Ha	Eggplant	Increased germination and yield	N, P, K, Mg and Ca supply	Najar et al. (2015)
	Fresh tissues	Maize	Increased yield	N, P, K and Ca supply	Jha (2021)
	Water, ethyl acetate, and methanol leaf extracts	–	Antimicrobial effect against *Pseudomonas aeruginosa* and *Staphylococcus aureus*	Phenols and flavonoids	

culinaris, wheat, maize, rapeseed, rice or sorghum, through the use of composts from *E. crassipes* (Osoro et al., 2014; Atere and Olayinka, 2019), *Azolla* (Ahmad and Tariq, 2021), *Arundo donax* (giant reed) (Kouki et al., 2016), *Typha latifolia* (broadleaf cattail) (Kouki et al., 2016), or *P. stratiotes* (Bhadha et al., 2016), among other macrophytes.

Another way to make nutrients from freshwater macrophyte biomass available to crops is through the use of vermicompost. From biomass from different origins, earthworms are capable of producing a resource of nutrients easily assimilated by plants (Yatoo et al., 2021). Some of the studies carried out with freshwater macrophytes have reported increases in germination, plant growth, nutrient content and productivity of different crops, such as eggplant, cucumber, *Abelmoschus esculentus* or

Vigna radiata, through the use of vermicompost from *Azolla*, *Eichhornia* (Gandhi and Sundari, 2012), or *Salvinia molesta* (kariba weed) (Hussain et al., 2018), among others. For the production of vermicompost from aquatic macrophytes, different species of earthworms are used, including *Eisenia fetida* (Najar et al., 2015), *Aporrectodea caliginosa trapezoides*, *Aporrectodea rosea rosea* (Najar and Khan, 2012), *Glossoscolex paulistus* or *Eudrilus eugeniae* (Kurian and Joseph, 2019).

Biochar is the result of subjecting biomass to a pyrolysis process, causing a thermal decomposition of the organic matter. Therefore, it is a resource that, when applied to crops, is capable of providing the soil with macronutrients (N, P and K) and micronutrients (Mg, Na, Mn, S, etc.) easily assimilated by plants. In addition, biochar improves soil structure, increasing its porosity and reducing its aggregation, increases water holding capacity, and favors the establishment and growth of soil biota, and even acts as a biopesticide of pathogens and agricultural pests. (Poveda et al., 2021). A study carried out in a cultivation field of *Pokkali*, the unique saline tolerant rice variety, by applying biochar from *E. crassipes* supposed an increase in root and shoot length, and plant height, due to the contribution of nutrients (Najmudeen et al., 2019).

4.2. Improvement of soil biology and structure

In addition to the direct contribution of nutrients, organic fertilizers can promote plant growth due to the presence of various microorganisms (Poveda et al., 2019). As far as compost from freshwater macrophytes is concerned, it has been determined how it is capable of increasing the growth of crops. such as *Brassica rapa* var. *perviridis.* due to the presence of plant growth promoting rhizobacteria (Matsuoka et al., 2020). Moreover, the compost from this plant biomass is capable of increasing quantity and diversity of phosphate solubilizing bacteria in soil (Matsuoka et al., 2019), or nodulation and N_2 fixation in legume crops, such as soybean (Atere et al., 2020).

The application of organic fertilizers to the field implies an improvement in the soil structure that results in a higher productivity of crops (Lekfeldt et al., 2017). Similarly, through the application of compost from *E. crassipes*, an increase in the growth of Chinese cabbage plants has been reported due to the improvement of the soil structure (Rakotoarisoa et al., 2020).

4.3. Phytoremediation

The ability of freshwater macrophytes to act as phytoremediation agents has been extensively described in the previous section. In the same way that freshwater macrophytes are capable of eliminating heavy metals and pollutants present in aquatic ecosystems by sorption, their tissues extract them from agricultural soil. In rice fields, the use of different *Azolla* species *in vivo* meant the elimination of up to 100% of heavy metals such as Cr, Cd, Cu, Zn and Hg, being accumulated in *Azolla*-tissues (Ahmad and Tariq, 2021). The application of compost from *E. crassipes* increased the growth of *Libidibia ferrea* in soils contaminated with heavy metals thanks to Fe, Mn, Cu, Zn, Cd, and Pb sorption (Gaudencio et al., 2018), as well as it happens with biochar, due to the presence of alkyl, carboxyl, phosphate and cyano groups that bind metals (Li et al., 2018). Other biochar from macrophytes, such as *P. australis* or *Thalia dealbata*, are capable of capturing contaminants that are very harmful to the agroecosystems, including hydrocarbons, such as phenanthrene (Wang et al., 2020), or drugs, such as sulphamethoxazole (Li et al., 2015). For both heavy metals and organic pollutants, biochar has been described as a stabilizing material. In the case of heavy metals, due to exchange with Ca^{2+}, Mg^{2+}, and other cations, the surface complexation with different functional groups, or the physical adsorption and surface precipitation. While for organic pollutants, the biochar acts by means of sorption (Zhang et al., 2013).

4.4. Sources of biological pesticides

When terrestrial plants are attacked by pathogens or herbivores, they activate hormonal pathways that lead to the accumulation of defense chemical compounds in a local and systemic way (Poveda, 2020), in the same way that happens with freshwater macrophytes (Morrison and Hay, 2011). In this sense, freshwater macrophyte leaves have been used to obtain antimicrobial extracts against plant pathogens such as *Pseudomonas aeruginosa* and *Staphylococcus aureus* bacteria, due to the presence of phenols and flavonoids (Jha, 2021). The n-butyl alcohol leaf extract from *E. crassipes* reported antimicrobial activity against the fungi plant pathogens *Alternaria alternata* and *Colletotrichum gloeosporioides*, and the bacteria *Bacillus subtilis*, due to the presence of phenols, alkaloids, flavonoids, glycosides, tannins and terpenoids. In addition, the application of this *E. crassipes*-extract in wheat plants led to a reduction in the field incidence of net blotch disease caused by *Pyrenophora teres* (Haggag et al., 2017).

5. Conclusions

The current rates of population growth require the search for alternatives towards the development of sustainable agriculture that allows supplying food in an environmental-friendly way. One of these alternatives could include the use of freshwater macrophytes as an agricultural resource, due to their ability to provide nutrients, improve the microbiota and soil structure, remove heavy metals and soil pollutants, or accumulate antimicrobial metabolites, due to whose mechanisms a promotion of plant growth and crop yield is achieved, and a decrease in the use of chemical fertilizers and in the development of diseases.

The current dispersal of exotic freshwater macrophytes in new ecosystems represents a serious problem, due to their rapid and massive growth. In this sense, their use as agricultural resources could substantially mitigate the costs associated with their elimination. An example of these affirmation are the numerous existing studies on the use of the invasive plant *E. crassipes* as an agricultural resource, with numerous benefits.

All the studies analyzed lead us to the conclusion that the freshwater macrophytes that are the most promising resources for use in agriculture, at least with the current studies, are: *Eichhornia crassipes*, *Hydrilla verticillata*, *Ceratophyllum demersum*, *Phragmites australis*, *Pistia stratiotes*, the genus *Azolla* and *Potamogeton maackianus*. In order to locate where these macrophytes are native or introduced species, and, therefore, where they are available for agricultural use, each macrophyte has been linked to its updated distribution map according to Plants of the World Online (http://plantsoftheworldonline.org/). In this sense, despite all the benefits outlined for the use of freshwater macrophytes as a resource in agriculture, there is an important limiting factor to consider: the presence of the macrophyte at the site where it is to be used. Although the use of freshwater macrophyte plant biomass in agriculture, when they pose an environmental problem due to their uncontrolled proliferation as invasive species, represents an important environmental, agricultural and economic benefit, it represents a finite natural resource and is not widely and homogeneously distributed around the planet.

6. Future perspectives

Many freshwater macrophytes are widely used in the phytoremediation of waters contaminated with heavy metals and other contaminants. The use of the biomass formed by these macrophytes as input for agriculture requires exhaustive studies on the flow of pollutants to the soil and crops.

Environmentally, the use of freshwater macrophytes as an agricultural resource implies the development of a circular economy linked to the need to eliminate these plants from various ecosystems. In addition, through the contribution of nutrients to crops when they are applied to the field and the absorption of leached nutrients when they grow in water bodies, their use in agriculture represents a significant reduction in the use of chemical fertilizers. Furthermore, it is important to highlight the role that the use of freshwater macrophytes can play in achieving carbon neutrality worldwide. These plants can contribute to climate change mitigation through carbon storage during their growth and then be used as a resource in agriculture.

With respect to rural areas with fewer resources, the possibility of using an accessible and cheap raw material as organic fertilizer can help in their economic development. The presence of aquatic ecosystems rich in freshwater macrophytes close to crop fields could be a continuous source of different benefits for their agricultural activity.

Another important focus of future research on the different effects of the use of freshwater macrophytes as an agricultural resource would be the analysis of the quality of the products obtained. In addition to increased crop productivity, the use of freshwater macrophytes can lead to important nutritional and nutraceutical improvements of these plant foods.

Author contribution

J.P. conceived and designed the manuscript. J.P. performed the bibliographic search and analyzed the information. J.P. wrote the manuscript and made the corresponding revisions.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

Abu, T., 2017. A review: aquatic macrophyte *Ceratophyllum demersum* L. (Ceratophyllaceae): plant profile, phytochemistry and medicinal properties. Int. J. Sci. Res. 6, 395–397. https://doi.org/10.21275/ART20174667.

Ahmad, N., Tariq, H., 2021. *Azolla* as waste decomposer and bio-fertilizer: a review. J. Appl. Res. Plant Sci. 2, 108–116. https://doi.org/10.38211/joarps.2021.2.1.14.

Akponikpè, P.I., Wima, K., Yacouba, H., Mermoud, A., 2011. Reuse of domestic wastewater treated in macrophyte ponds to irrigate tomato and eggplant in semi-arid West-Africa: benefits and risks. Agric. Water Manag. 98, 834–840. https://doi.org/10.1016/j.agwat.2010.12.009.

Alencar, B.T.B., Ribeiro, V.H.V., Cabral, C.M., dos Santos, N.M.C., Ferreira, E.A., Francino, D.M.T., et al., 2020. Use of macrophytes to reduce the contamination of water resources by pesticides. Ecol. Indicat. 109, 105785 https://doi.org/10.1016/j.ecolind.2019.105785.

Alkimin, G.D., Daniel, D., Frankenbach, S., Serôdio, J., Soares, A.M.V.M., Barata, C., Nunes, B., 2019. Evaluation of pharmaceutical toxic effects of non-standard endpoints on the macrophyte species *Lemna minor* and *Lemna gibba*. Sci. Total Environ. 657, 926–937. https://doi.org/10.1016/j.scitotenv.2018.12.002.

Atere, C.T., Olayinka, A., 2019. Enhancing maize (*Zea mays* l.) growth and nutrient uptake via application of water hyacinth (*Eichornia crassipes* [Mart.] Solms) compost and inorganic nutrients. Niger J. Soil Sci. 29, 27–34. https://doi.org/10.36265/njss.2019.290105.

Atere, C.T., Osunde, M.O., Olayinka, A., 2020. Microbial dynamics and nutrient mineralization in soil amended with cacao pod and water hyacinth composts: implication for nitrogen fixed by soybean. Commun. Soil Sci. Plant Anal. 51, 2466–2478. https://doi.org/10.1080/00103624.2020.1836202.

Augustynowicz, J., Grosicki, M., Hanus-Fajerska, E., Lekka, M., Waloszek, A., Kołoczek, H., 2010. Chromium (VI) bioremediation by aquatic macrophyte *Callitriche cophocarpa* Sendtn. Chemosphere 79, 1077–1083. https://doi.org/10.1016/j.chemosphere.2010.03.019.

Baer-Nawrocka, A., Sadowski, A., 2019. Food security and food self-sufficiency around the world: a typology of countries. PLoS One 14. https://doi.org/10.1371/journal.pone.0213448 e0213448.

Basheer, A.A., 2018a. Chemical chiral pollution: impact on the society and science and need of the regulations in the 21st century. Chirality 30, 402–406. https://doi.org/10.1002/chir.22808.

Basheer, A.A., 2018b. New generation nano-adsorbents for the removal of emerging contaminants in water. J. Mol. Liq. 261, 583–593. https://doi.org/10.1016/j.molliq.2018.04.021.

Bashir, I., Bhat, R.A., Mir, S.A., 2020. Applications of macrophytes as environmentally sound technique for cleaning of contaminated ecosystems. In: Bioremediation and Biotechnology. Springer, Cham, pp. 269–290.

Bhadha, J.H., Alvarez, O., Lang, T.A., Giurcanu, M.C., Daroub, S.H., 2016. Growth efficacy of sorghum and rice amended with dried versus composted aquatic vegetation. Sustain. Agric. Res. 5, 92–102. https://doi.org/10.22004/ag.econ.234996.

Bondoc, C., 2020. Nutrient restoration capacity of *Eichhornia crassipes* compost on a nutrient-depleted soil. Int. J. Environ. Sci. 5, 1–5.

Bornette, G., Puijalon, S., 2009. Macrophytes: ecology of aquatic plants. In: Encyclopedia of Life Sciences. John Wiley and Sons, Chichester, pp. 1–9. https://doi.org/10.1002/9780470015902.a0020475.

Brundu, G., 2015. Plant invaders in European and Mediterranean inland waters: profiles, distribution, and threats. Hydrobiologia 746, 61–79. https://doi.org/10.1007/s10750-014-1910-9.

Calabi-Floody, M., Medina, J., Rumpel, C., Condron, L.M., Hernandez, M., Dumont, M., de la Luz Mora, M., 2018. Smart fertilizers as a strategy for sustainable agriculture. Adv. Agron. 147, 119–157. https://doi.org/10.1016/bs.agron.2017.10.003.

Carnaje, N.P., Talagon, R.B., Peralta, J.P., Shah, K., Paz-Ferreiro, J., 2018. Development and characterisation of charcoal briquettes from water hyacinth (*Eichhornia crassipes*)-molasses blend. PLoS One 13, e0207135. https://doi.org/10.1371/journal.pone.0207135.

Ceschin, S., Zuccarello, V., Caneva, G., 2010. Role of macrophyte communities as bioindicators of water quality: application on the Tiber River basin (Italy). Plant Biosyst. 144, 528–536. https://doi.org/10.1080/11263500903429221.

Chukwuka, K.S., Omotayo, O.E., 2008. Effects of *Tithonia* green manure and water hyacinth compost application on nutrient depleted soil in South-Western Nigeria. Int. J. Soil Sci. 3, 69–74.

Ciecierska, H., Kolada, A., 2014. ESMI: a macrophyte index for assessing the ecological status of lakes. Environ. Monit. Assess. 186, 5501–5517. https://doi.org/10.1007/s10661-014-3799-1.

Crist, E., Mora, C., Engelman, R., 2017. The interaction of human population, food production, and biodiversity protection. Science 356, 260–264. https://doi.org/10.1126/science.aal2011.

Delaqua, G.C.G., Marvila, M.T., Souza, D., Rodriguez, R.J.S., Colorado, H.A., Vieira, C.M.F., 2020. Evaluation of the application of macrophyte biomass *Salvinia auriculata* Aublet in red ceramics. J. Environ. Manag. 275, 111253 https://doi.org/10.1016/j.jenvman.2020.111253.

Demars, B.O., Edwards, A.C., 2007. Tissue nutrient concentrations in freshwater aquatic macrophytes: high inter-taxon differences and low phenotypic response to nutrient supply. Freshw. Biol. 52, 2073–2086. https://doi.org/10.1111/j.1365-2427.2007.01817.x.

Dogan, M., Karatas, M., Aasim, M., 2018. Cadmium and lead bioaccumulation potentials of an aquatic macrophyte *Ceratophyllum demersum* L.: a laboratory study. Ecotoxicol. Environ. Saf. 148, 431–440. https://doi.org/10.1016/j.ecoenv.2017.10.058.

da Silva-Santos, J., da Silva Pontes, M., Grillo, R., Fiorucci, A.R., de Arruda, G.J., Santiago, E.F., 2020. Physiological mechanisms and phytoremediation potential of the macrophyte Salvinia biloba towards a commercial formulation and an analytical standard of glyphosate. Chemosphere 259, 127417. https://doi.org/10.1016/j.chemosphere.2020.127417.

Demers, E., Kõiv-Vainik, M., Yavari, S., Mench, M., Marchand, L., Vincent, J., et al., 2020. Macrophyte potential to treat leachate contaminated with wood preservatives: plant tolerance and bioaccumulation capacity. Plants 9, 1774. https://doi.org/10.3390/plants9121774.

Dos Anjos, M.L., Henares, M.N.P., Bória-Fernandez, J.A., 2018. Use of *Eichhornia crassipes* dry matter as organic substrate for germination and initial growth of corn. Eco. Rec. Agropec. 5, 97–102. https://doi.org/10.19136/era.a5n13.1139.

Elo, M., Alahuhta, J., Kanninen, A., Meissner, K.K., Seppälä, K., Mönkkönen, M., 2018. Environmental characteristics and anthropogenic impact jointly modify aquatic macrophyte species diversity. Front. Plant Sci. 9, 1001. https://doi.org/10.3389/fpls.2018.01001.

Farias, W.M., de Andrade, L.A., Pereira, E.D., Dias, B.O., de Albuquerque, M.B., da Silva Fraga, V., 2013. Physical and chemical properties of substrates produced using macrophytes aquatics. Semina Ciências Agrárias 34, 3257–3270. https://doi.org/10.5433/1679-0359.2013v34n6Supl1p3257.

Farooq, M., Rehman, A., Pisante, M., 2019. Sustainable agriculture and food security. In: Innovations in Sustainable Agriculture. Springer, Cham, pp. 3–24.

Fernandes, K.D., Cañote, S.J.B., Ribeiro, E.M., Thiago Filho, G.L., Fonseca, A.L., 2019. Can we use Cd-contaminated macrophytes for biogas production? Environ. Sci. Pollut. Res. 26, 27620–27630. https://doi.org/10.1007/s11356-018-2318-2.

Food and Agricultural Organization (FAO), 2009. "How to feed the world: global agriculture towards 2050". www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf.

Gandhi, A., Sundari, U.S., 2012. Effect of vermicompost prepared from aquatic weeds on growth and yield of eggplant (*Solanum melongena* L.). J. Biofert. Biopestic. 3, 128. https://doi.org/10.4172/2155-6202.1000128.

Gaudencio, H.D.S., de Morais, E.R.C., Maia, C.E., da Costa, M.V., Nogueira, H.C., 2018. Use of pottery ash and organic compound of aquatic macrophyte in degraded soil recovery: evaluation of heavy metals. Ambiência 14, 356–369.

Grasset, C., Abril, G., Mendonça, R., Roland, F., Sobek, S., 2019. The transformation of macrophyte-derived organic matter to methane relates to plant water and nutrient contents. Limnol. Oceanogr. 64, 1737–1749. https://doi.org/10.1002/lno.11148.

Guedes-Alonso, R., Montesdeoca-Esponda, S., Herrera-Melián, J.A., Rodríguez-Rodríguez, R., Ojeda-González, Z., Landívar-Andrade, V., et al., 2020. Pharmaceutical and personal care product residues in a macrophyte pond-constructed wetland treating wastewater from a university campus: presence, removal and ecological risk assessment. Sci. Total Environ. 703, 135596 https://doi.org/10.1016/j.scitotenv.2019.135596.

Haggag, M.W., Abou El Ella, S.M., Abouziena, H.F., 2017. Phytochemical analysis, antifungal, antimicrobial activities and application of *Eichhornia crassipes* against some plant pathogens. Planta Daninha 35, 1–11. https://doi.org/10.1590/s0100-83582017350100026.

Han, Z., Cui, B., 2016. Performance of macrophyte indicators to eutrophication pressure in ponds. Ecol. Eng. 96, 8–19. https://doi.org/10.1016/j.ecoleng.2015.10.019.

Han, S., Li, J., Zhou, Q., Liu, G., Wang, T., 2019. Harmless disposal and resource utilization of wastes from the lake in China: dewatering, composting and safety evaluation of fertilizer. Algal Res. 43, 101623 https://doi.org/10.1016/j.algal.2019.101623.

Hassan, A., Nawchoo, I.A., 2020. Impact of invasive plants in aquatic ecosystems. In: Bioremediation and Biotechnology. Springer, Cham, pp. 55–73.

Hassanien, R., Husein, D.Z., Al-Hakkani, M.F., 2018. Biosynthesis of copper nanoparticles using aqueous *Tilia* extract: antimicrobial and anticancer activities. Heliyon 4, e01077. https://doi.org/10.1016/j.heliyon.2018.e01077.

Hofstra, D., Schoelynck, J., Ferrell, J., Coetzee, J., de Winton, M., Bickel, T.O., et al., 2020. On the move: new insights on the ecology and management of native and alien macrophytes. Aquat. Bot. 162, 103190 https://doi.org/10.1016/j.aquabot.2019.103190.

Human, L.R., Snow, G.C., Adams, J.B., Bate, G.C., Yang, S.C., 2015. The role of submerged macrophytes and macroalgae in nutrient cycling: a budget approach. Estuar. Coast Shelf Sci. 154, 169–178. https://doi.org/10.1016/j.ecss.2015.01.001.

Hussain, N., Abbasi, T., Abbasi, S.A., 2018. Generation of highly potent organic fertilizer from pernicious aquatic weed *Salvinia molesta*. Environ. Sci. Pollut. Res. 25, 4989–5002. https://doi.org/10.1007/s11356-017-0826-0.

Jain, M.S., Kalamdhad, A.S., 2018a. Efficacy of batch mode rotary drum composter for management of aquatic weed (*Hydrilla verticillata* (Lf) Royle). J. Environ. Manag. 221, 20–27. https://doi.org/10.1016/j.jenvman.2018.05.055.

Jain, M.S., Kalamdhad, A.S., 2018b. A review on management of *Hydrilla verticillata* and its utilization as potential nitrogen-rich biomass for compost or biogas production. Bioresour. Technol. Rep. 1, 69–78. https://doi.org/10.1016/j.biteb.2018.03.001.

Janker, J., Mann, S., Rist, S., 2018. What is sustainable agriculture? Critical analysis of the international political discourse. Sustainability 10, 4707. https://doi.org/10.3390/su10124707.

Jha, Y., 2021. Macrophytes as a potential tool for crop production by providing nutrient as well as protection against common phyto pathogen. Highlights BioSci. 4, 1–5. https://doi.org/10.36462/H.BioSci.202103.

Kang, S.M., Adhikari, A., Bhatta, D., Gam, H.J., Gim, M.J., Son, J.I., et al., 2022. Comparison of effects of chemical and food waste-derived fertilizers on the growth and nutrient content of lettuce (*Lactuca sativa* L.). Resources 11, 21. https://doi.org/10.3390/resources11020021.

Kannadasan, N., Natarajan, N., Anbusaravanan, N., Sekar, P., Krishnamoorthy, R., 2013. Assessment of sustainable vermiconversion of water hyacinth by *Eudrilus eugeniae* and *Eisenia fetida*. J. Nat. Appl. Sci. 5, 451–454. https://doi.org/10.31018/jans.v5i2.352.

Karthikeya, K., Sarma, M.K., Ramkumar, N., Subudhi, S., 2020. Exploring optimal strategies for aquatic macrophyte pre-treatment: sustainable feedstock for biohydrogen production. Biomass Bioenergy 140, 105678. https://doi.org/10.1016/j.biombioe.2020.105678.

Kolada, A., 2010. The use of aquatic vegetation in lake assessment: testing the sensitivity of macrophyte metrics to anthropogenic pressures and water quality. Hydrobiologia 656, 133–147. https://doi.org/10.1007/s10750-010-0428-z.

Kolada, A., Willby, N., Dudley, B., Nõges, P., Søndergaard, M., Hellsten, S., et al., 2014. The applicability of macrophyte compositional metrics for assessing eutrophication in European lakes. Ecol. Indicat. 45, 407–415. https://doi.org/10.1007/s10750-010-0428-z.

Kolhe, S.S., Singh, A.K., 2019. A brief review on *Eichhornia* extract as liquid fertilizers for aquaculture pond. Int. J. Curr. Microbiol. App. Sci. 8, 1044–1051. https://doi.org/10.20546/ijcmas.2019.803.127.

Kouki, S., Saidi, N., M'hiri, F., Hafiane, A., Hassen, A., 2016. Co-Composting of macrophyte biomass and sludge as an alternative for sustainable management of constructed wetland by-products. Clean–Soil Air Water 44, 694–702. https://doi.org/10.1002/clen.201500346.

Kuhar, U., Germ, M., Gaberščik, A., Urbanič, G., 2011. Development of a River Macrophyte Index (RMI) for assessing river ecological status. Limnologica 41, 235–243. https://doi.org/10.1016/j.limno.2010.11.001.

Kurian, D., Joseph, P.V., 2019. Vermicomposting of phytoremediated *Eichornia crassipes* as an alternative management of biodegradable wastes and water pollution. Americ. Int. J. Res. Formal Appl. Nat. Sci. 19, 59–62.

Lekfeldt, J.D.S., Kjaergaard, C., Magid, J., 2017. Long-term effects of organic waste fertilizers on soil structure, tracer transport, and leaching of colloids. J. Environ. Qual. 46, 862–870. https://doi.org/10.2134/jeq2016.11.0457.

Li, T., Han, X., Liang, C., Shohag, M.J.I., Yang, X., 2015. Sorption of sulphamethoxazole by the biochars derived from rice straw and alligator flag. Environ. Technol. 36, 245–253. https://doi.org/10.1080/09593330.2014.943299.

Li, Q., Tang, L., Hu, J., Jiang, M., Shi, X., Zhang, T., et al., 2018. Removal of toxic metals from aqueous solution by biochars derived from long-root *Eichhornia crassipes*. R. Soc. Open Sci. 5, 180966 https://doi.org/10.1098/rsos.180966.

Li, C., Wang, M., Luo, X., Liang, L., Han, X., Lin, X., 2019. Accumulation and effects of uranium on aquatic macrophyte *Nymphaea tetragona* Georgi: potential application to phytoremediation and environmental monitoring. J. Environ. Radioact. 198, 43–49. https://doi.org/10.1016/j.jenvrad.2018.12.018.

Macreadie, P.I., Trevathan-Tackett, S.M., Baldock, J.A., Kelleway, J.J., 2017. Converting beach-cast seagrass wrack into biochar: a climate-friendly solution to a coastal problem. Sci. Total Environ. 574, 90–94. https://doi.org/10.1016/j.scitotenv.2016.09.021.

Mamolos, A.P., Nikolaidou, A.E., Pavlatou-Ve, A.K., Kostopoulou, S.K., Kalburtji, K.L., 2011. Ecological threats and agricultural opportunities of the aquatic cane-like grass *Phragmites australis* in wetlands. In: Genetics, Biofuels and Local Farming Systems. Springer, Dordrecht, pp. 251–275.

Markich, S.J., 2013. Water hardness reduces the accumulation and toxicity of uranium in a freshwater macrophyte (*Ceratophyllum demersum*). Sci. Total Environ. 443, 582–589. https://doi.org/10.1016/j.scitotenv.2012.11.038.

Martínez-Nieto, P., Bernal-Castillo, J., Calixto-Díaz, M., Basto-Riaño, D., Angélica, M., Chaparro-Rico, B., 2011. Biofertilizers and composting accelerators of polluting macrophytes of a Colombian lake. J. Soil Sci. Plant Nutr. 11, 47–61. https://doi.org/10.4067/S0718-95162011000200005.

Matsuoka, S., Suzuki, Y., Hobara, S., Osono, T., 2018. Fungal succession and decomposition of composted aquatic plants applied to soil. Fungal Ecol. 35, 34–41. https://doi.org/10.1016/j.funeco.2018.06.005.

Matsuoka, S., Fujinaga, S., Kobayashi, Y., Hobara, S., Osono, T., 2019. Bacterial 16S rDNA and alkaline phosphatase gene diversity in soil applied with composted aquatic plants. Limnology 21, 357–364. https://doi.org/10.1007/s10201-019-00594-y.

Matsuoka, S., Kobayashi, Y., Hobara, S., Osono, T., 2020. Identifying microbial drivers promoting plant growth on soil amended with composted aquatic plant: insight into nutrient transfer from aquatic to terrestrial systems. Limnology 21, 443–452. https://doi.org/10.1007/s10201-020-00613-3.

Mebane, C.A., Simon, N.S., Maret, T.R., 2014. Linking nutrient enrichment and streamflow to macrophytes in agricultural streams. Hydrobiologia 722, 143–158. https://doi.org/10.1007/s10750-013-1693-4.

Mees, J.B., Gomes, S.D., Boas, M.A.V., Fazolo, A., Sampaio, S.C., 2009. Removal of organic matter and nutrients from slaughterhouse wastewater by using *Eichhornia crassipes* and evaluation of the generated biomass composting. Eng. Agrícola 29, 466–473. https://doi.org/10.1590/S0100-69162009000300013.

Morrison, W.E., Hay, M.E., 2011. Induced chemical defenses in a freshwater macrophyte suppress herbivore fitness and the growth of associated microbes. Oecologia 165, 427–436. https://doi.org/10.1007/s00442-010-1791-1.

Murphy, K., Efremov, A., Davidson, T.A., Molina-Navarro, E., Fidanza, K., Betiol, T.C.C., et al., 2019. World distribution, diversity and endemism of aquatic macrophytes. Aquat. Bot. 158, 103127 https://doi.org/10.1016/j.aquabot.2019.06.006.

Najar, I.A., Khan, A.B., 2012. Vermicomposting of fresh water weeds (macrophytes) by *Eisenia fetida* (Savigny, 1826), *Aporrectodea caliginosa trapezoides* (Duges, 1828) and *Aporrectodea rosea rosea* (Savigny, 1826). Dyn. Soil Dyn. Plant 6, 73–77.

Najar, I.A., Khan, A.B., 2013. Management of fresh water weeds (macrophytes) by vermicomposting using *Eisenia fetida*. Environ. Sci. Pollut. Res. 20, 6406–6417. https://doi.org/10.1007/s11356-013-1687-9.

Najar, I.A., Khan, A.B., Hai, A., 2015. Effect of macrophyte vermicompost on growth and productivity of brinjal (*Solanum melongena*) under field conditions. Int. J. Recycl. Org. Waste Agric. 4, 73–83. https://doi.org/10.1007/s40093-015-0087-1.

Najmudeen, T.M., Arakkal Febna, M.A., Rojith, G., Zacharia, P.U., 2019. Characterisation of biochar from water hyacinth *Eichhornia crassipes* and the effects of biochar on the growth of fish and paddy in integrated culture systems. J. Coast Res. 86, 225–234. https://doi.org/10.2112/SI86-033.1.

Naseem, S., Bhat, S.U., Gani, A., Bhat, F.A., 2021. Perspectives on utilization of macrophytes as feed ingredient for fish in future aquaculture. Rev. Aquacult. 13, 282–300. https://doi.org/10.1111/raq.12475.

Nunes, B., Pinto, G., Martins, L., Gonçalves, F., Antunes, S.C., 2014. Biochemical and standard toxic effects of acetaminophen on the macrophyte species *Lemna minor* and *Lemna gibba*. Environ. Sci. Pollut. Res. 21, 10815–10822. https://doi.org/10.1007/s11356-014-3059-5.

Osoro, N., Muoma, J.O., Amoding, A., Mukaminega, D., Muthini, M., Ombori, O., Maingi, J.M., 2014. Effects of water hyacinth (*Eichhornia crassipes* [mart.] solms) compost on growth and yield parameters of maize (*Zea mays*). Curr. J. Appl. Sci. Technol. 4, 617–633. https://doi.org/10.9734/BJAST/2014/5776.

Owamah, H.I., Enaboifo, M.A., Izinyon, O.C., 2014. Treatment of wastewater from raw rubber processing industry using water lettuce macrophyte pond and the reuse of its effluent as biofertilizer. Agric. Water Manag. 146, 262–269. https://doi.org/10.1016/j.agwat.2014.08.015.

Pérez, D.J., Okada, E., Menone, M.L., Costa, J.L., 2017. Can an aquatic macrophyte bioaccumulate glyphosate? Development of a new method of glyphosate extraction in *Ludwigia peploides* and watershed scale validation. Chemosphere 185, 975–982. https://doi.org/10.1016/j.chemosphere.2017.07.093.

Pi, N., Ng, J.Z., Kelly, B.C., 2017. Bioaccumulation of pharmaceutically active compounds and endocrine disrupting chemicals in aquatic macrophytes: results of hydroponic experiments with *Echinodorus horemanii* and *Eichhornia crassipes*. Sci. Total Environ. 601, 812–820. https://doi.org/10.1016/j.scitotenv.2017.05.137.

Plumecocq, G., Debril, T., Duru, M., Magrini, M.B., Sarthou, J.P., Therond, O., 2018. The plurality of values in sustainable agriculture models. Ecol. Soc. 23, 21. https://doi.org/10.5751/ES-09881-230121.
Pondei, J.O., Ogugbue, C.J., Okpokwasili, G.C., 2018. Endophyte-assisted rhizoremediation of petroleum by the aquatic macrophyte, *Commelina benghalensis*, in the wetlands of the Niger Delta Region, Nigeria. J. Environ. Sci. Toxicol. Food Technol. 12, 57–65. https://doi.org/10.9790/2402-1205015765.
Poveda, J., Jiménez-Gómez, A., Saati-Santamaría, Z., Usategui-Martín, R., Rivas, R., García-Fraile, P., 2019. Mealworm frass as a potential biofertilizer and abiotic stress tolerance-inductor in plants. Appl. Soil Ecol. 142, 110–122. https://doi.org/10.1016/j.apsoil.2019.04.016.
Poveda, J., 2020. Use of plant-defense hormones against pathogen-diseases of postharvest fresh produce. Physiol. Mol. Plant Pathol. 111, 101521 https://doi.org/10.1016/j.pmpp.2020.101521.
Poveda, J., 2021. Insect frass in the development of sustainable agriculture. A review. Agron. Sustain. Dev. 41, 1–10. https://doi.org/10.1007/s13593-020-00656-x.
Poveda, J., Martínez Gómez, Á., Fenoll, C., Escobar, C., 2021. The use of biochar for plant-pathogen control. Phytopathol. https://doi.org/10.1094/PHYTO-06-20-0248-RVW.
Queiroz, R.C.S., Andrade, R.S., Dantas, I.R., Ribeiro, V.D.S., Neto, L.B.R., Almeida Neto, J.A.D., 2017. Use of native aquatic macrophytes in the reduction of organic matter from dairy effluents. Int. J. Phytoremediation 19, 781–788. https://doi.org/10.1080/15226514.2017.1284750.
Rakotoarisoa, T., Richter, T., Schmidt, N., Contreras, J.M., 2020. An alternative for agriculture at Lake Alaotra, Madagascar: organic fertilizer and soil amendment from the invasive water hyacinth (*Eichhornia crassipes*). Madag. Conserv. Dev. 15, 27–34.
Rather, M.A., Khan, N.S., Gupta, R., 2017a. Hydrothermal carbonization of macrophyte *Potamogeton lucens* for solid biofuel production: production of solid biofuel from macrophyte *Potamogeton lucens*. Eng. Sci. Technol. Int. J. 20, 168–174. https://doi.org/10.1016/j.jestch.2016.08.015.
Rather, M.A., Khan, N.S., Gupta, R., 2017b. Catalytic hydrothermal carbonization of invasive macrophyte Hornwort (*Ceratophyllum demersum*) for production of hydrochar: a potential biofuel. Int. J. Environ. Sci. Technol. 14, 1243–1252. https://doi.org/10.1007/s13762-016-1227-5.
Röhl, M., Roth, S., Schütz, W., Zehnsdorf, A., Herbes, C., 2019. Biogas production from submerged macrophytes-a case study of regional biomass potentials in Germany. Energy Sustain. Soc. 9, 1–12. https://doi.org/10.1186/s13705-019-0204-5.
Shaji, H., Chandran, V., Mathew, L., 2021. Organic fertilizers as a route to controlled release of nutrients. In: Controlled Release Fertilizers for Sustainable Agriculture. Academic Press, pp. 231–245.
Sharma, A., Kumar, V., Shahzad, B., Tanveer, M., Sidhu, G.P.S., Handa, N., et al., 2019. Worldwide pesticide usage and its impacts on ecosystem. SN Appl. Sci. 1, 1–16. https://doi.org/10.1007/s42452-019-1485-1.
Shukla, A., Shukla, S., Hodges, A.W., Harris, W.G., 2020. Valorization of farm pond biomass as fertilizer for reducing basin-scale phosphorus losses. Sci. Total Environ. 720, 137403 https://doi.org/10.1016/j.scitotenv.2020.137403.
Shyam, S., Das, T., Kumar, G.P., 2020. Co-composting invasive aquatic macrophytes and pond sediment holds the potential for environmental amelioration: selecting the right shade of grey. Acta Ecol. Sin. https://doi.org/10.1016/j.chnaes.2020.12.004.
Singh, R., Tripathi, R.D., Dwivedi, S., Kumar, A., Trivedi, P.K., Chakrabarty, D., 2010. Lead bioaccumulation potential of an aquatic macrophyte *Najas indica* are related to antioxidant system. Bioresour. Technol. 101, 3025–3032. https://doi.org/10.1016/j.biortech.2009.12.031.
Singh, J., Kalamdhad, A.S., 2015. Assessment of compost quality in agitated pile composting of water hyacinth collected from different sources. Int. J. Recycl. Org. Waste Agric. 4, 175–183. https://doi.org/10.1007/s40093-015-0097-z.
Singh, T.B., Ali, A., Prasad, M., Yadav, A., Shrivastav, P., Goyal, D., Dantu, P.K., 2020. Role of organic fertilizers in improving soil fertility. In: Contaminants in Agriculture. Springer, Cham, pp. 61–77.
Soloviy, K., Malovanyy, M., 2019. Freshwater ecosystem macrophytes and microphytes: development, environmental problems, usage as raw material. Review. Environ. Problems 3, 115–124. https://doi.org/10.1371/journal.pone.0126677.
Song, U., 2017. Post-remediation use of macrophytes as composting materials for sustainable management of a sanitary landfill. Int. J. Phytoremediation 19, 395–401. https://doi.org/10.1080/15226514.2016.1244156.
Song, U., Song, U., 2019. Improvement of soil properties and plant responses by compost generated from biomass of phytoremediation plant. Environ. Eng. Res. 25, 638–644. https://doi.org/10.4491/eer.2019.59.
Su, W., Sun, Q., Xia, M., Wen, Z., Yao, Z., 2018. The resource utilization of water hyacinth (*Eichhornia crassipes* [mart.] Solms) and its challenges. Resources 7, 46. https://doi.org/10.3390/resources7030046.
Stabenau, N., Zehnsdorf, A., Rönicke, H., Wedwitschka, H., Moeller, L., Ibrahim, B., Stinner, W., 2018. A potential phosphorous fertilizer for organic farming: recovery of phosphorous resources in the course of bioenergy production through anaerobic digestion of aquatic macrophytes. Energy Sustain. Soc. 8, 1–10. https://doi.org/10.1186/s13705-018-0155-2.
Tazart, Z., Douma, M., Tebaa, L., Loudiki, M., 2019. Use of macrophytes allelopathy in the biocontrol of harmful *Microcystis aeruginosa* blooms. Water Supply 19, 245–253. https://doi.org/10.2166/ws.2018.072.
Ugya, A.Y., Imam, T.S., Ma, J., 2019. Mini-review on the efficacy of aquatic macrophytes as mosquito larvicide. J. Appl. Bot. Food Qual. 92, 320–326. https://doi.org/10.5073/JABFQ.2019.092.043.
Wagner, G.M., Mshigeni, K.E., 1986. The *Utricularia-Cyanophyta* association and its nitrogen-fixing capacity. Hydrobiologia 141, 255–261. https://doi.org/10.1007/BF00014219.
Wang, X., Guo, Z., Hu, Z., Ngo, H., Liang, S., Zhang, J., 2020. Adsorption of phenanthrene from aqueous solutions by biochar derived from an ammoniation-hydrothermal method. Sci. Total Environ. 733, 139267 https://doi.org/10.1016/j.scitotenv.2020.139267.
Xian, Q., Hu, L., Chen, H., Chang, Z., Zou, H., 2010. Removal of nutrients and veterinary antibiotics from swine wastewater by a constructed macrophyte floating bed system. J. Environ. Manag. 91, 2657–2661. https://doi.org/10.1016/j.jenvman.2010.07.036.
Xie, W.Y., Huang, Q., Li, G., Rensing, C., Zhu, Y.G., 2013. Cadmium accumulation in the rootless macrophyte *Wolffia globosa* and its potential for phytoremediation. Int. J. Phytoremediation 15, 385–397. https://doi.org/10.1080/15226514.2012.702809.
Xue, P.Y., Yan, C.Z., 2011. Arsenic accumulation and translocation in the submerged macrophyte *Hydrilla verticillata* (Lf) Royle. Chemosphere 85, 1176–1181. https://doi.org/10.1016/j.chemosphere.2011.09.051.
Yatoo, A.M., Ali, M.N., Baba, Z.A., Hassan, B., 2021. Sustainable management of diseases and pests in crops by vermicompost and vermicompost tea. A review. Agron. Sustain. Dev. 41, 1–26. https://doi.org/10.1007/s13593-020-00657-w.
Yongabi, K., Nagabhatla, N., Rios, P.C.S., 2018. Phytoremediation eco-models using indigenous macrophytes and phytomaterials. In: Multifunctional Wetlands. Springer, Cham, pp. 253–273.
Zhang, X., Uroic, M.K., Xie, W.Y., Zhu, Y.G., Chen, B.D., McGrath, S.P., et al., 2012. Phytochelatins play a key role in arsenic accumulation and tolerance in the aquatic macrophyte *Wolffia globosa*. Environ. Pollut. 165, 18–24. https://doi.org/10.1016/j.envpol.2012.02.009.
Zhang, X., Wang, H., He, L., Lu, K., Sarmah, A., Li, J., et al., 2013. Using biochar for remediation of soils contaminated with heavy metals and organic pollutants. Environ. Sci. Pollut. Res. 20, 8472–8483. https://doi.org/10.1007/s11356-013-1659-0.
Zhao, B., Xing, P., Wu, Q.L., 2020. Interactions between bacteria and fungi in macrophyte leaf litter decomposition. Environ. Microbiol. https://doi.org/10.1111/1462-2920.15261.